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Study on the characteristics of biomass for co-combustion in coal power plant

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Abstract In this study, a torrefaction experiment was carried out using domestic woody biomass (waste wood and logging residue) and overseas herbaceous biomass (PKS: palm kernel shell and bagasse). Torrefaction was performed in a nitrogen atmosphere using a batch-type apparatus, either with changing torrefaction temperature or with changing duration at a constant temperature. Here, only the oxygen contained in the biomass was used in the torrefaction experiment. The physical and chemical properties of biomass fuels produced under various torrefaction conditions were investigated to determine their characteristics as fuels for coal firing power plant. Based on thermogravimetric analysis (TGA), proximate analysis of four kinds of biomass, and the result of varying the torrefaction temperature and duration, each of the biomass residues was torrefied for 30 min at a temperature range of 250–350 °C in an anaerobic conditions. Consequently, when compared with the raw material, each of the torrefied materials showed lower moisture and volatile matter content, fixed carbon and ash content, and higher calorific value.

Keywords Biomass · Torrefaction · Combustion · RPS (renewable portfolio standards)

Introduction

Owing to the exhaustion of fossil fuels and the economic and environmental problems, it is necessary to develop alternative energy sources that can replace fossil energy. Recently, there has been steadily increasing research and interest in the use of non-food biomass as an alternative energy source. Biomass energy refers to energy that is converted from organisms and by-products thereof to liquid, gas, and solid fuels or to electrical and thermal energy [1–3]. The torrefaction process in this study is a potential heat treatment method for obtaining high-quality fuel from biomass. Torrefaction is a process in which oxygen is removed by exposing a torrefaction gas decreasing the calorific value, such as carbon dioxide, water, and organic acid, at a temperature range of 200–300 °C. Compared with pure biomass, torrefied materials have lower moisture content and O/C ratio, and thus have high energy density and calorific value that can be utilized as fuels [4, 5]. In order to stably mix and combust produced torrefied biomass with coal in a coal firing power plant, the combusting (mixed combustion) characteristics of the torrefied biomass, and the standardization and quality stabilization of biomass pellet manufacturing facilities are important. An appropriate quality standard and quality management plan are also necessary to prevent adverse effects on the environment and combustion apparatus, which may occur upon mixed combustion of the biomass fuel and coal [6–8]. Particularly, in order to develop mixed combustion as part of coal power generation, further research is required on the fuel characteristics of biomass by-products. Therefore, to determine the applicability of torrefied materials as solid fuels, it is necessary to carry out an overall review of their fuel properties. To address the issues mentioned above, the

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present study produced biomass fuels through torrefaction of biomass, including domestic wood residue and domestic and overseas agricultural by-products. The resulting materials then underwent proximate analysis, ultimate analysis, and analysis for moisture content, calorific value, ash-fusion temperature, and heavy metal content. These analyses quantified the properties and combustion characteristics of the biomass sources and the torrefied biomass fuels.

Experimental materials and methods

The experiments on the torrefaction of biomass utilized both domestic and overseas feedstocks. Domestic woody biomass comprised logging residue and plentiful waste wood containing various heavy metals, whereas overseas herbaceous biomass comprised PKS (palm kernel shell) and bagasse as raw materials, thus four kinds of biomass were used (Fig. 1).

Figure 2 shows a system for the torrefaction process. A 20 g sample of material was taken in a ceramic boat and placed into an electric furnace. Torrefaction was conducted in a nitrogen atmosphere at predetermined temperature and duration, and the gas given off was analyzed in real time using a gas analyzer. After arriving at the predetermined temperature or duration, the boat was removed from the furnace, the weight change in the sample was measured, and component analysis and calorific value analyses were performed. The electric furnace had a maximum operation temperature of 1,600 °C, an inner tube having a diameter of 150 mm and a length of 600 mm, and a 3-zone proportional-integral-derivative (PID) temperature controller.

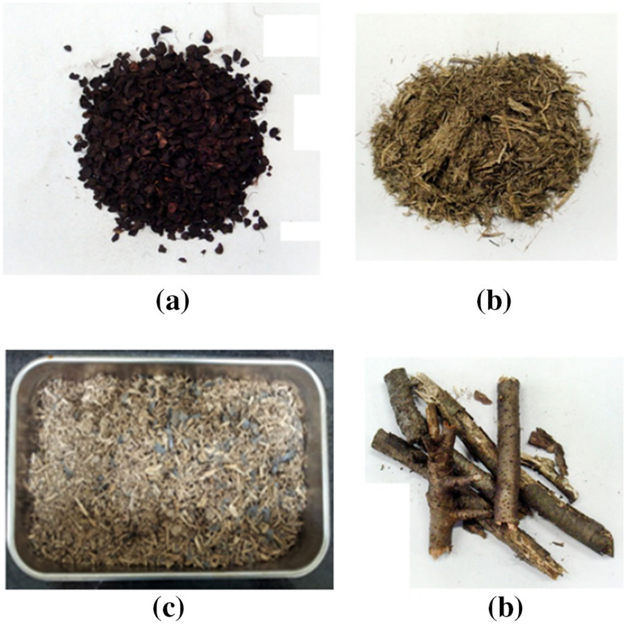


Fig. 1 Image of biomass: **a** PKS, **b** bagasse, **c** waste wood, **d** logging residue

The proximate analysis was carried out before and after torrefaction, using a TGA-701 proximate analyzer (LECO Co., USA). The analysis method referred to a quality standard test method for solid fuels, measuring moisture, volatile matter, ash, and mixed carbon contents. The ultimate analysis used an ASTM-D5291 device, and the heavy metal analysis (Thermo, ICAP 6000) for Cd, Pb, Cr, Hg, and As contents was carried out before and after torrefaction. Calorific value was determined using a calorimeter (Farr 1261, EA calorimeter), and TGA analysis was performed in a reducing atmosphere (nitrogen, 75 ml/min) using a thermal analysis system (TGA851e Mettler-Toledo). The pyrolysis characteristics were analyzed via three heating rates (β) of 10, 20, and 30 °C/min, while non-isothermally heating from room temperature to 600 °C. Each torrefied sample was put in a desiccator (SK-C003) that controlled temperature and humidity, in order to compare and analyze the extent of moisture reabsorption during storage and transportation.

Results and discussion

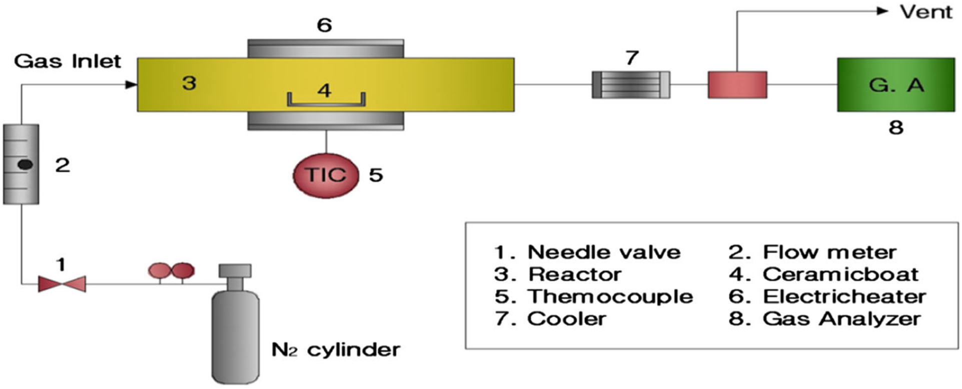
Thermogravimetric analysis

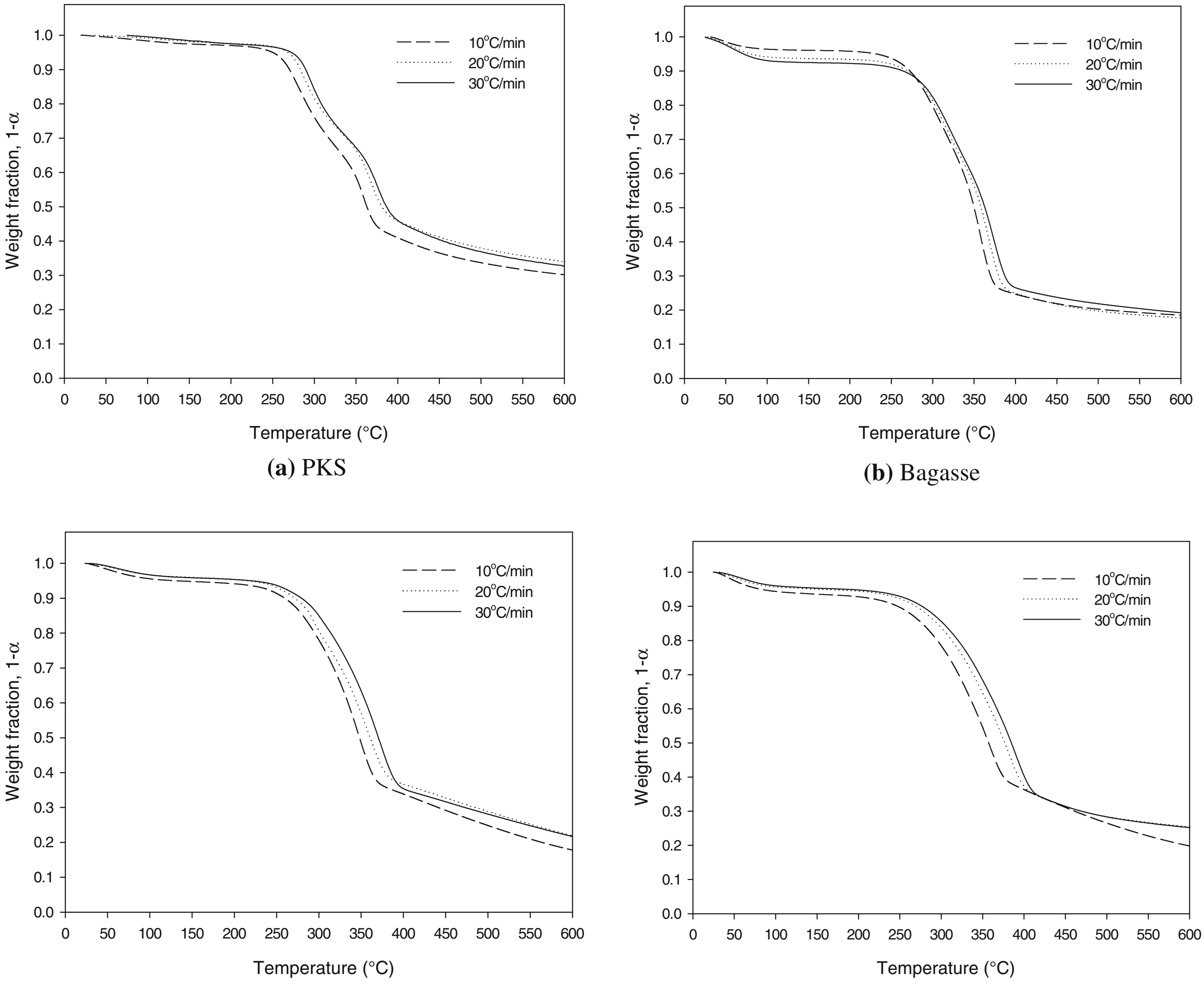
Figure 3 shows TGA for the samples that were torrefied under nitrogen atmosphere at the three different heating rates. The TGA curve shows that each sample is slowly pyrolyzed and combusted over a temperature range of about 200–500 °C. Each sample showed weight loss at temperatures between 250 °C and approximately 400 °C, although there is some difference. The TGA results in Fig. 3 confirm the weight reduction range. However, from the perspective of the energy yield ratio of the torrefied biomass, excessive weight reduction results in a very low energy yield ratio. Therefore, the torrefied biomass is generally produced under conditions that provide an optimal energy yield ratio, considering the calorific value and the components of the torrefied biomass. The pyrolysis reaction of the torrefied biomass (from 250 to 400 °C) shows pyrolysis characteristics of cellulose as a main component. It is known that the weight reduction of torrefied biomass occurs by breaking hydrogen bond structures and C–O and C–C bond structures in the cellulose through thermal drying at about 200 °C or more [2, 3].

Proximate/ultimate/heavy metal analysis

A wood fuel that recently received attention due to the renewable portfolio standards (RPS) system showed

Fig. 2 Schematic diagram of the apparatus





(a) PKS

(b) Bagasse

(c) Waste wood

(d) Logging residues

Fig. 3 TGA analysis of torrefaction biomass

various problems such as low energy density, high transportation cost and low economic feasibility, storage problems due to moisture absorption, insufficient timber resource, and difficulty in molding. Therefore, in order to overcome the above problems, a torrefaction technology is proposed that operates at a temperature of 250–350 °C less than that of the pyrolysis temperature for complete carbonization. The torrefaction technology treats the biomass under high-temperature anaerobic conditions and reduces a hydroxyl group of the biomass so that the biomass has hydrophobic properties, thereby solving the problems of moisture reabsorption during storage or transportation. Furthermore, the process enhances the calorific value and thus high-efficiency solid fuels can be manufactured.

The analysis of combustibles and ash content according to biomass samples and torrefaction temperatures is indicated in Table 1. The combustibles contain volatile matter and fixed carbon, and it is assumed that moisture is entirely removed. In an optimal fuel, combustibles content is high but ash content is low. In the present study, the ash contents were 8.7 % for PKS at 350 °C, 8.8 % for bagasse at 350 °C, 1.7 % for the waste wood at the lowest temperature of 250 °C, and 5.3 % for the logging residue at 300 °C. If the torrefaction temperature is increased to 400 °C or more, C-containing components in the volatile matter are combusted and the ash content is increased, and thus the biomass cannot be used as a fuel.

The optimal results of the biomass sample and the torrefied biomass are indicated in Table 2. Table 1 shows the optimal temperature for conducting torrefaction. In order to check the characteristics of the materials for use as fuels, the measured combustibles content is divided into volatile matter content and fixed carbon content, and the moisture content is also measured. The torrefaction temperature of the biomass was 350 °C for PKS, 350 °C for bagasse, 250 °C for waste wood, and 300 °C for logging residue. The experimental results showed that torrefaction at a temperature range of 250–350 °C reduced the moisture contents from 11.43 to 0.14 % for PKS, from 11.02 to 0.18 % for bagasse, from 10.77 to 2.05 % for waste wood, and from 10.12 to 2.73 % for logging residue. All four of the materials showed increases in ash content, from about 3 % or less to 8.70 % for PKS, 8.72 % for bagasse, 1.70 % for waste wood, and 6.45 % for logging residue. All materials showed increased fixed carbon content of 26.23, 26.24, 31.79, and 27.20 %, respectively; the waste wood showed the greatest increase (about 213 %), and the PKS the smallest increase (about 12 %). Following torrefaction, the fixed carbon content was increased but the volatile matter content was reduced by 5–10 %. During torrefaction, the fibrous structure of the biomass is partially broken down from heavy cellulose into smaller molecular structures. Therefore, the biomass samples can be easily ground, and their properties change from hydrophilic to hydrophobic.

Following torrefaction, all four types of biomass showed an upper calorific value of ≥21,085 kJ/kg and a lower calorific value of at least 19,762 kJ/kg. It seems that the increase in calorific value even in response to low-temperature heat treatment is due to the reduction in the moisture content. The calorific values obtained in this study satisfy the total calorific contents specified for torrefied woody biomass (21,085 kJ/kg) and herbaceous biomass (21,625 kJ/kg) in the draft ISO/TC 238 [9, 10].

According to the quality standards for torrefied pellet products defined by the United States Department of Energy and the National Renewable Energy Laboratory [11, 12], and the European quality standards defined in 2010 by the KEMA (N.V. tot Keuring van Electrotechnische Materialen), which was led by the Dutch Government, the moisture content should be 1–5 %, calorific value should be 20,000 kJ/kg or more, volatile matter content should be 55–65 %, and fixed carbon content should be 28–35 %. The torrefied biomass produced in this study satisfies the specified values for volatile matter, moisture, and ash contents, but the fixed carbon content was about 1 % less.

Tables 3 and 4 compare the ultimate analysis and heavy metal analysis for the four types of biomass before and

Table 1 Combustibles and ash analysis of biomass with torrefaction temperature

Dry (°C)	PKS		Bagasse		Waste wood		Logging residue	
	Combustibles	Ash	Combustibles	Ash	Combustibles	Ash	Combustibles	Ash
Raw	92.01	7.99	97.92	2.08	98.20	1.80	96.93	3.07
150	90.79	9.21	97.10	2.90	98.73	1.27	96.57	3.43
200	88.25	11.75	96.43	3.57	98.28	1.72	96.27	3.73
250	89.49	10.51	97.10	2.90	98.35	1.65	95.88	4.12
300	90.11	9.89	96.63	3.37	98.11	1.89	94.65	5.35
350	91.32	8.68	91.21	8.79	96.49	3.51	90.11	9.89
400	80.18	19.82	89.60	10.40	95.89	4.11	83.57	16.43
450	73.79	26.21	75.48	24.52	95.46	4.54	81.61	18.39
500	57.18	42.82	60.21	39.79	95.92	4.08	79.05	20.95
550	63.51	36.49	59.43	40.57	93.38	6.62	82.98	17.02
600	57.42	42.58	56.88	43.12	92.51	7.49	76.50	23.50

Table 2 Proximate analysis and heating value of torrefaction biomass

Sample	Temperature (°C)	Moisture (%)	Volatile (%)	Ash (%)	Fixed carbon (%)	HHV (LHV) (kJ/kg)
PKS	Raw	11.43	64.64	0.91	23.02	18,623 (17,593)
	350	0.14	64.93	8.70	26.23	22,441 (21,474)
Bagasse	Raw	11.02	71.07	2.80	15.11	18,355 (17,045)
	350	0.18	64.86	8.72	26.24	21,625 (20,863)
Waste wood	Raw	10.77	74.00	0.33	14.90	20,670 (19,326)
	250	2.05	64.46	1.70	31.79	21,085 (19,762)
Logging residue	Raw	10.12	69.39	0.75	19.74	21,185 (19,833)
	300	2.73	63.62	6.45	27.20	22,031 (20,980)

HHV higher heating value, *LHV* lower heating value

Table 3 Ultimate analysis of torrefaction biomass

Samples	Temperature (°C)	C (%)	H (%)	N (%)	O (%)	S (%)	Cl (%)
PKS	Raw	43.39	5.18	0.95	50.35	0.06	0.06
	350	69.82	4.58	0.57	24.79	0.06	0.05
Bagasse	Raw	47.53	6.44	0.94	45.01	0.08	ND
	350	48.22	5.84	1.03	44.88	0.03	ND
Waste wood	Raw	47.50	5.97	3.11	42.78	0.07	0.58
	250	47.55	6.08	4.52	41.69	0.05	0.11
Logging residue	Raw	51.59	6.52	0.83	40.96	0.11	ND
	320	54.48	5.32	1.15	39.01	0.04	ND

ND not determined

Table 4 Heavy metal analysis of torrefaction biomass

Samples	Temperature (°C)	Cd (mg/kg)	Pb (mg/kg)	Cr (mg/kg)	Hg (mg/kg)	As (mg/kg)
PKS	Raw	ND	ND	ND	ND	ND
	350	ND	ND	28.13	ND	ND
Bagasse	Raw	ND	ND	0.29	0.05	ND
	350	ND	ND	0.33	0.07	ND
Waste wood	Raw	20.02	16.02	4.61	ND	ND
	250	24.51	22.17	7.34	ND	ND
Logging residue	Raw	ND	ND	0.48	0.07	0.16
	320	ND	ND	2.18	0.42	1.47

ND not determined

after torrefaction. Oxygen and hydrogen contents are reduced in all four kinds of biomass following torrefaction, but nitrogen components are increased. Sulfur components are generally reduced, but chlorine components are increased. Particularly, the sulfur and nitrogen components show similar results to those for coal. Therefore, it seems that airborne contaminants may not be increased when such materials are mixed and combusted with coal. Meanwhile, the high carbon contents are required to obtain high-quality fuels. The results demonstrate that the carbon components are increased in all biomass samples.

In the heavy metal analysis, the Cr content of torrefied PKS is 28.13 mg/kg. Following torrefaction, the Cr and Hg contents of bagasse are 0.33 mg/kg and 0.07 mg/kg, respectively; Cd is 24.51 mg/kg, Pb is 22.17 mg/kg, and Cr is 7.34 mg/kg in waste wood; Cr is 2.18 mg/kg, Hg is 0.42 mg/kg, and As is 0.147 mg/kg in the logging residue. Therefore, it seems that, with the exception of the waste wood, the three other types of biomass do not display problems associated with heavy metal content. In case of waste wood with high levels of Cd, this heavy metal is involved in raw material. Therefore, it seems that the heavy metal contents might vary greatly according to the kinds of waste woods. Additionally, the concentrations of heavy metals are greatly increased following torrefaction, because the volume of the biomass is reduced. With the exception of the waste wood, the three other types of biomass satisfied the domestic quality standards for biomass-solid fuels.

Basic characteristics of fuels

Figure 4 shows the fuel ratio (fixed carbon/volatile matter) and the combustibility index (CI) [13] of the torrefied biomass samples. The fuel ratio can be obtained from the proximate analysis result, and the CI is as follows. The CI can be used to evaluate the suitability of the material for mixed combustion in coal-fired thermal power plants. A CI of the mixed fuel with coal less than 12,560 kJ/kg or more than 23,030 kJ/kg is inappropriate. The fuel ratio of the biomass sample increases from 0.2 before torrefaction to 0.4 or more afterwards. Although the fuel ratio of the biomass sample is less than that of subbituminous coal (0.5–1.0) used in thermoelectric power plants, it seems that the fuel ratio can be mixed within a range of 5 % of the total amount of the coal and then combusted with the coal. In order to increase the fuel ratio, it is necessary to increase the torrefaction temperature, reduce the volatile matter, and then increase the fixed carbon. However, in this case, even

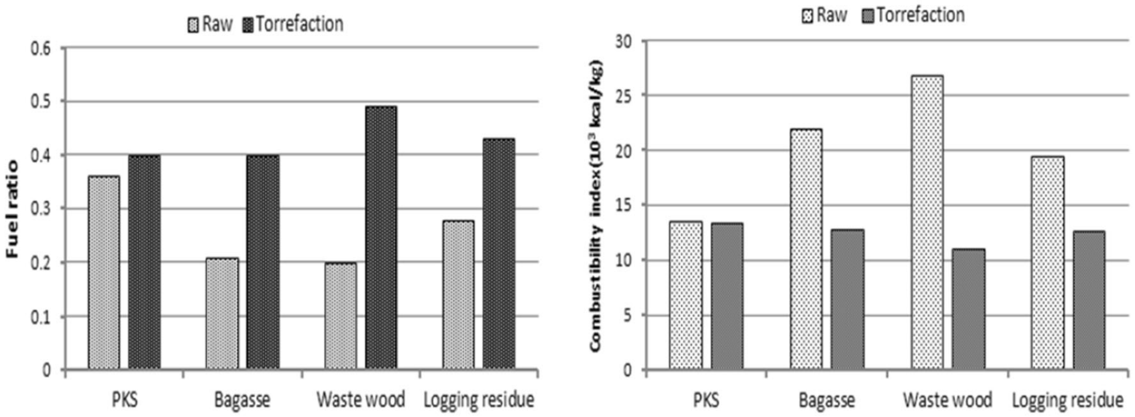


Fig. 4 Fuel ratio and combustibility index of biomass

though the fuel ratio is increased, its value as a fuel is greatly reduced due to the considerable increase in ash content.

$$\mathrm{CI}\,(\mathrm{kcal/kg}) = \frac{\text{dried high calorific value}}{\text{fuel ratio}} \times (115 - \text{ash}) \times \frac{1}{105}$$

The four types of biomass show pre-torrefaction CIs ranging from 56,819 kJ/kg for PKS to 112,110 kJ/kg or more for waste wood. After torrefaction, the CI of each biomass sample is reduced to within the range 46,055–54,428 kJ/kg. Therefore, it seems that the appropriate CI can be maintained if the mixing ratio with coal is optimized.

Results of moisture reabsorption

The four kinds of torrefied biomass were maintained for about 15 days at 21 ± 2 °C and 78 ± 2 % humidity; the changes in the moisture content of each sample are shown in Fig. 5. In the herbaceous biomass samples (PKS/bagasse), the moisture content sharply increased during the first 7 days but there were few changes after 11 days. In the woody biomass samples (waste wood/logging residue), the moisture content continuously increased for 11 days, after which there was no further change, and the moisture content did not show the sharp increase that was observed in the herbaceous biomass samples. Figure 5 shows that when about twice the minimum moisture content was reabsorbed, the moisture content did not increase further. Since the torrefied biomass materials are mainly manufactured in Southeast Asia where the raw materials originate, the moisture reabsorption problem should be taken into consideration throughout the entire production and transportation processes.

Experimental materials and methods

The results of the ash-fusion temperature analysis are shown in Table 5 and Fig. 6. In order to solve the problem of secondary contamination by materials generated during subsequent combustion of the torrefied biomass, research is required on the melting technology of the combusted materials and each biomass material. In the melting technology, the melting temperature of each of the combusted materials is a very important factor. The ash-fusion temperature was analyzed using an ash-fusion temperature analyzer (CKIC, AF-4000). An ash sample formed into a pyramid was placed into the electric furnace and then heated at a rate of 10 °C/min in an oxygen atmosphere. The deformed states of the sample were categorized as initial deformation temperature (IDT), spherical temperature (ST), hemispherical temperature (HT), and fluid temperature (FT). The analysis was carried out from about 900 to 1600 °C according to ASTM standards.

The fluid temperatures for the torrefaction samples were 1,351 °C for PKS, 1,220 °C for bagasse, 1,295 °C for waste wood, and 1,270 °C for logging residue. PKS has the highest melting point. The ΔT (melt starting point) for each of the four materials were 194 °C for PKS, 83 °C corn stack, for 75 °C for waste wood, and 56 °C for the logging residue. Therefore, since the range of melting points is very narrow, the melting process should be carefully operated to reflect the sudden melting temperature. If the ash-fusion temperature is low, the combustion efficiency of a boiler is also reduced. Thus, it is preferable to operate at higher ash-fusion temperature.

Analysis of torrefaction characteristics

Figure 7 shows the torrefaction characteristics of the PKS and the bagasse. In order to check the torrefaction

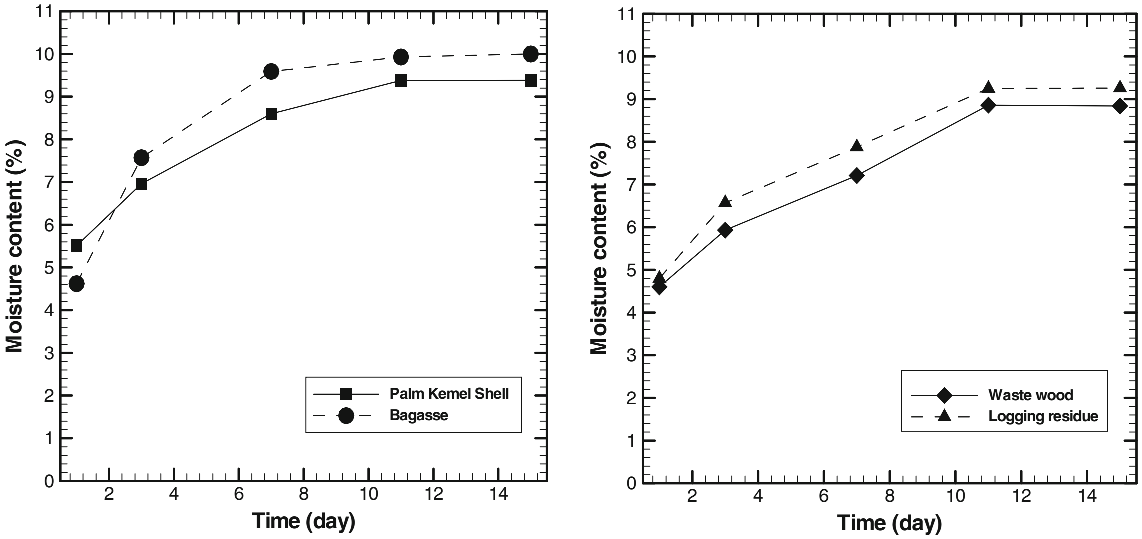


Fig. 5 Water reabsorption curve of torrefaction biomass (PKS/bagasse/waste wood/logging residue)

Table 5 Comparison of ash-fusion torrefaction biomass

Sample name	IDT (°C)	ST (°C)	HT (°C)	FT (°C)	ΔT (FT-DT) (°C)	Atmospheric condition
PKS	1,157	1,125	1,288	1,315	194	Oxidative
Bagasse	1,137	1,163	1,188	1,220	83	
Waste wood	1,220	1,263	1,276	1,295	75	
Logging residue	1,214	1,238	1,243	1,270	56	

IDT initial deformation temperature, *ST* spherical temperature, *HT* hemispherical temperature, *FT* fluid temperature

characteristics, the CO content, C_XH_Y content, a high calorific value, a low calorific value or the like were measured according to the torrefaction temperatures, and the energy yield ratio was calculated using the following equation:

$$E_{\mathrm{char}} = M_{\mathrm{char}} \times \left(\frac{\mathrm{HHV}_{\mathrm{char}}}{\mathrm{HHV}_{\mathrm{char}}}\right) E_{\mathrm{char}}$$

where

$\mathrm{HHV}_{\mathrm{char}}/\mathrm{HHV}_{\mathrm{char}}$ is the maximum calorific value of the torrefaction products and the raw materials.

The product yield ratio M_{char} is calculated by the following equation:

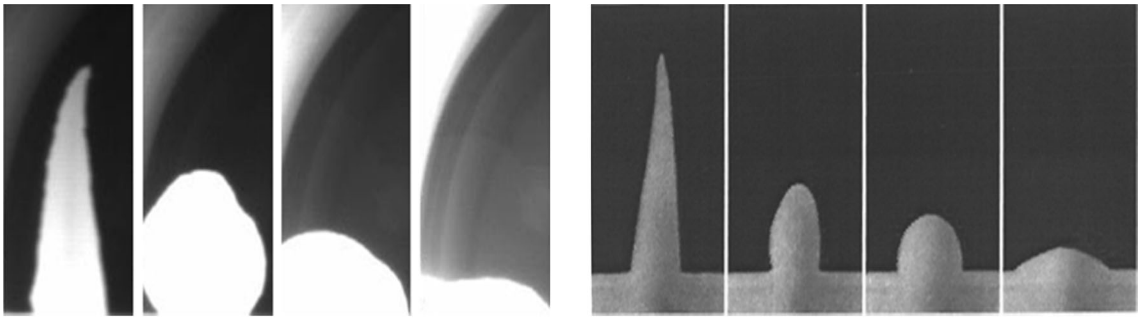
$$M_{\mathrm{char}} = (C_{\mathrm{char}}/D_{\mathrm{raw}}),$$

where C_{char} is the weight of the torrefaction product and D_{raw} is the dried weight of the raw material. It can be understood that both kinds of herbaceous biomass start to be torrefied from about 300 °C at which CO and C_XH_Y are generated, and the minimum calorific value (18,841 kJ/kg) of the torrefaction product is achieved at about 300 °C. Furthermore, an energy yield ratio of $\geq$80 % is maintained. However, since excessive torrefaction temperature results in increased ash and lower energy yield ratio, it is preferable to conduct torrefaction at a temperature range of 250–300 °C.

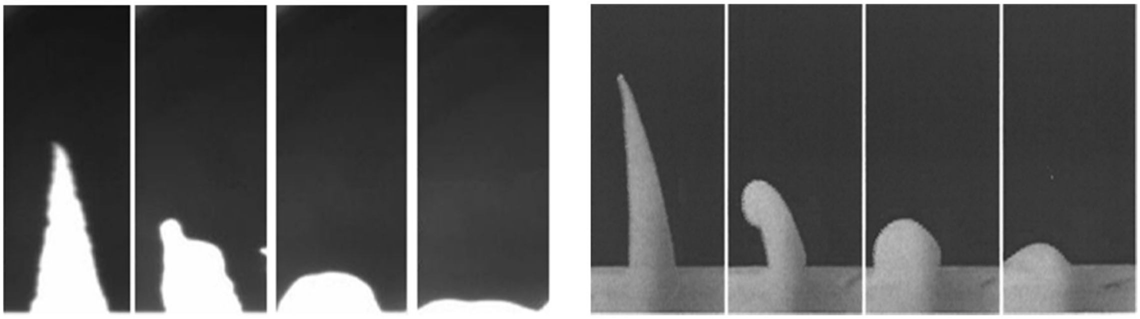
Figure 8 shows the torrefaction characteristics of the waste wood and the logging residue. The dried samples have high calorific values due to the characteristics of the woody biomass. When considering how to improve transportation efficiency through increased energy density, and how to vary the properties of the biomass to minimize biodegradability and improve storability, we conclude that torrefaction should be conducted at a minimum temperature of 300 °C, since CO and C_XH_Y are generated at 300–320 °C. However, in the case of the woody biomass materials, the products are useful as fuels, whereas in the case of the waste wood, reduction technology is required to deal with heavy metal contents.

Conclusions

The biomass by-products used in this experiment were categorized as domestic woody by-products and overseas herbaceous by-products. The domestic woody by-products comprised waste wood and logging residue, and the overseas herbaceous by-products comprised PKS and bagasse. The four kinds of biomass were subjected to torrefaction under various conditions, and the physical and chemical properties of the resulting products were investigated to determine their characteristics as biomass fuels. The characteristics of torrefied biomass for coal firing power plant were investigated. The results of a torrefaction experiment are summarized below:



(a) PKS **(b)** Bagasse



(c) Waste wood **(d)** Logging residues

Fig. 6 Ash-fusion analysis of torrefaction biomass (PKS/bagasse/waste wood/logging residues)

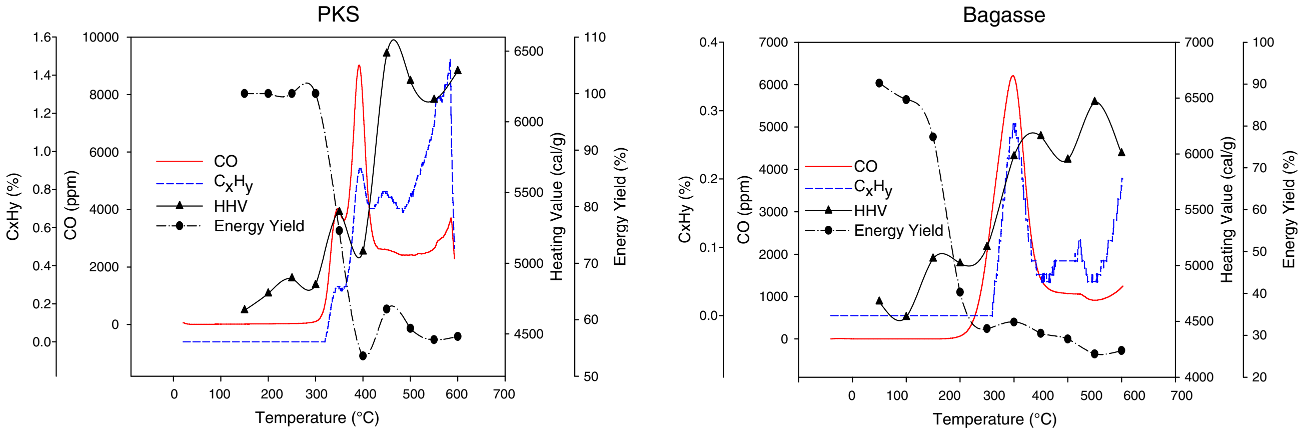


Fig. 7 Torrefaction characteristics of PKS/bagasse

1. In the thermogravimetric analysis (TGA), each sample was slowly pyrolyzed and combusted over a temperature range of about 200–500 °C, and the weight of each sample was sharply reduced at 250–400 °C. On the basis of the TGA, the torrefaction experiment was carried out at 250–350 °C.
2. The optimal torrefaction temperature for each type of biomass is 350 °C for PKS, 350 °C for bagasse, 250 °C for waste wood, and 300 °C for logging residue. Compared with the raw materials, the moisture content and volatile matter of each torrefied material are reduced, but the fixed carbon, ash content, and thus the calorific value are increased. Among the four types of biomass, heavy metals are detected only in the waste wood. The calorific values following torrefaction range from 21,085 to 22,441 kJ/kg, which satisfies the standards for the draft version of ISO/TC 238.
3. Following torrefaction, the fuel ratio is 0.40–0.48, and combustible index (CI) is from 45,854 to 54,191 kJ/kg.

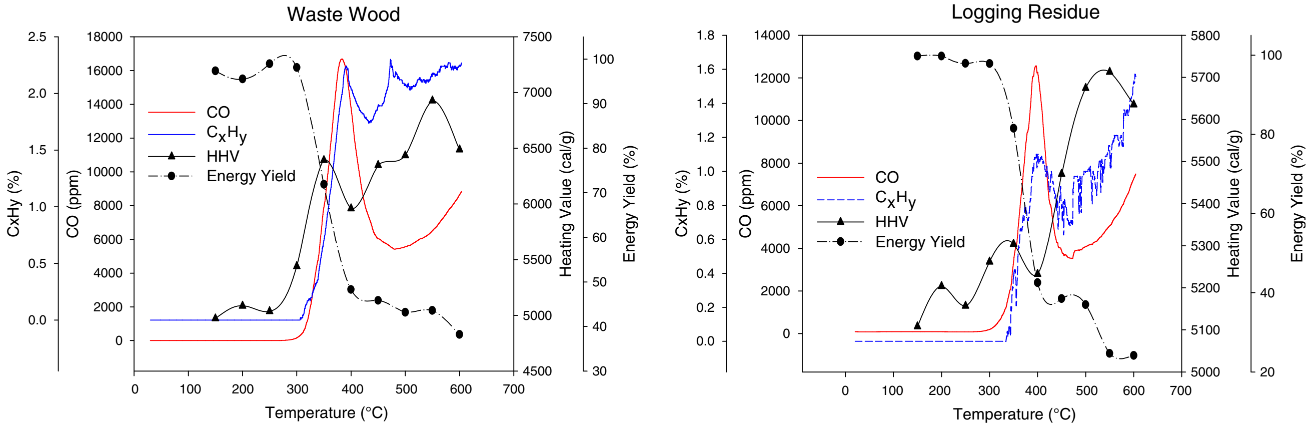


Fig. 8 Torrefaction characteristics of waste wood/logging residues

When torrefied biomass was combusted with coal, the CI can be maintained by optimizing the mixing ratio with coal.

4. The fluid temperature for each torrefaction sample is 1,351 °C for PKS, 1,220 °C for bagasse, 1,295 °C for waste wood, and 1,270 °C for logging residue. As seen, the bagasse has the lowest melting point, and the PKS has the highest melting point. Also, in the ΔT (melt starting point) for each material is 194 °C for PKS, 83 °C for bagasse, 75 °C for the waste wood, and 56 °C for the logging residue.
5. Water reabsorption tests on the torrefied materials showed that moisture content is initially 4–5 %, increasing up to 10 % after 11 days.
6. The range of heavy metals(Cd, Pb, Cr, Hg and As) contents in torrefied biomass is 0.33–28.13 mg/kg. The Cd content in torrefied waste wood is 24.51 mg/kg which is over standards for biomass-solid fuels (Cd: 5.0 mg/kg). With the exception of the waste wood, the three other types of biomass (PKS, bagasse and logging residue) satisfied the domestic quality standards for biomass-solid fuels.

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